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The Opaque Minerals of the Ultramafic Rocks of New Caledonia

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The ultramafic rocks of New Caledonia contain a diversity of disseminated ore minerals in non-economic amounts. Eighteen opaque minerals are described herein with pentlandite, millerite and heazelwoodite most prominent. Several new or unusual mineralogical features are recorded. These include an eutectic intergrowth between pentlandite and primary chalcocite, reaction between pentlandite and chalcocite to form chalcopyrite and millerite, exsolution intergrowth between pentlandite and millerite, between pentlandite and mackinawite and between millerite and cubanite. In the formation of the garnieritic ores of New Caledonia some of the nickel would appear to have been derived from the breakdown of disseminated sulphides as well as from the nickel inherent in the silicate minerals of the ultramafic rocks.

Les roches ultramafiques de la Nouvelle-Calédonie comportent une diversité de mineraux disséminés dans des quantités sous-économiques. Dix-huit minéraux opaques y sont décrites avec la proéminence de la pentlandite et la millerite. Quelques caractéristiques minéralogiques, nouvelles et exceptionelles, sont notées. Ceci comprend un enchevêtrement eutectique entre la pentlandite et la chalcopyrite primaire, une réaction entre la pentlandite et la chalcocite qui se changent en chalcopyrite et en millerite, un entredéveloppement par l'exsolution entre la pentlandite et la machinawite et entre la millérite et la cubanite. Il est établi que, pendant la formation du minérais garniéritique de la Nouvelle-Calédonie une part du nickel vient des sulphures disséminées de même que du nickel naissant dans les silicates des roches ultramafiques.

Introduction

The ultramafic rocks of New Caledonia comprise a sequence of hartzburgite, dunite and pyroxenite with associated sheets of serpentinite and are referred to as "ultramafic massifs" (Routhier 1951; Avias 1955, 1967; Lillie and Brothers 1970; Guillon and Routhier 1971). These rocks occupy a total area of some 7,000 sq. Km. (Fig. 1) and are distributed throughout the length of the island. In the western part of the island the rocks are spread along a synclinal axis as a series of isolated massifs; the greater part of the southern half of the island is covered by a thick mass of these rocks. This, the "Main Ultramafic Mass" is some 3,000 m thick.

The serpentinite occurs along fault zones and along the contact with underlying formations. This contact is either horizontal or dips toward the NNE at from 10°, on the west coast, to 50° on the east coast.

The ultramafic rocks rest upon Upper-Eocene thoeliitic basalts, in part, or upon folded sedimentary rocks of Cretaceous age, and elsewhere of Eocene age, with strong unconformity (Guillon 1972a).

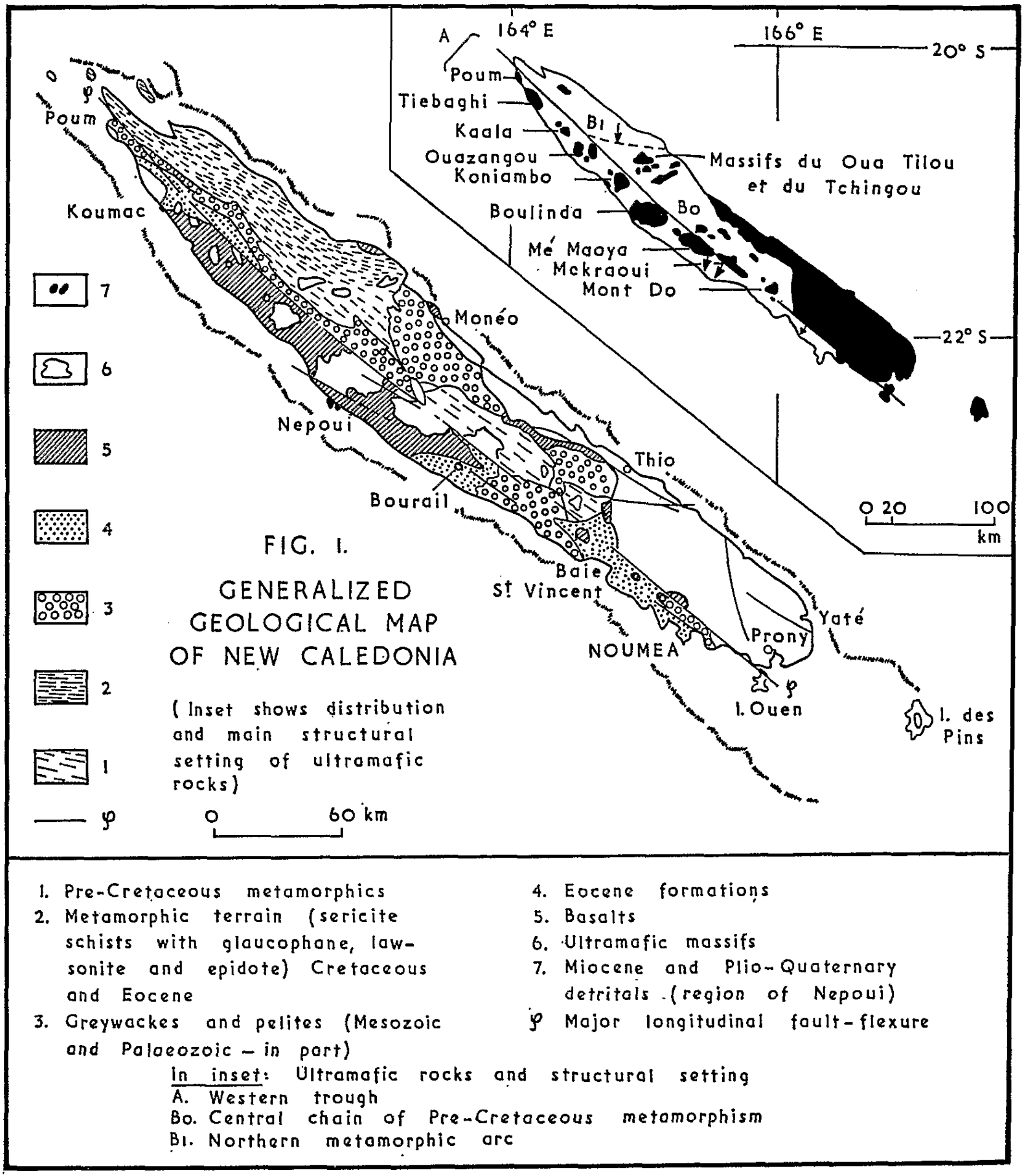

Fig. 1. Geological map of New Caledonia

The age of emplacement of the ultramafites is given as Oligocene (GUILLON 1972b) and there are reasons to believe that both the ultramafic rocks and the basalts are comagmatically related and arise from a parent picritic magma of non-alkali character (CHALLIS and GUILLON 1971).

This paper serves to record the occurrence, in non-economic amounts, of a diverse assemblage of ore minerals in the ultramafic rocks of New Caledonia, including a number of rare and unusual mineral intergrowths. Sampling was carried out at a sufficient number of localities to infer that sulphides are sparsely distributed over a wide area within the ultramafites.

The ultramafic rocks

The essential rock type is a fine to medium grained hartzburgite within which are innumerable layers of dunitic and pyroxenitic fractionates. So profuse is this layering, in places, that on slightly weathered surfaces the rock assumes a quite banded appearance (Fig. 2).

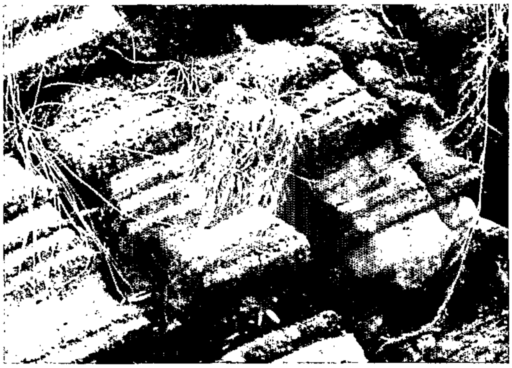

Fig. 2. Rhythmical alternation of pyroxenite, hartzburgite and dunite, Main Massif, New Caledonia

The hartzburgite shows a uniform composition throughout and comprises forsteritic olivine Fo 92 (65 per cent), enstatite En 90 (30 per cent) and chromite (5 per cent). Small chromite seams occur occasionally in the dunitic layers of the upper part of the ultramafic mass.

The banding follows a rhythmical sequence which ranges, from bottom to top, as follows:

1. orthopyroxenite,
2. pyroxene-rich hartzburgite,
3. pyroxene-poor hartzburgite,
4. dunite, sometimes with small podiform chromite segregations.

Each of the above sequence ranges, in total, from about 1 m to several meters in vertical extent.

The layering is mostly discordant to the basal contact of the massifs, often at a high angle, and this suggests the possibility that some, at least, of these massifs are large nappe structures. The sequence indicated above (1 to 4) is the reverse of that normally encountered in layered ultramafic masses; some overturning during thrusting is therefore indicated.

The Main Ultramafic Mass is intruded, in places, by dykes of quartz diorite and of adamellite.

Ore minerals

Sparsely disseminated sulphides occur in each sequence of the lower 1000 m, or so, of the ultramafic mass (GUILLON and SAOS 1971). The sulphides are found mainly in the orthopyroxenite and, to a lesser extent, in the pyroxene-rich hartzburgite. Most of the sulphides appear to be generally synmagmatic; some of them are late- or epi-magmatic alteration products and, in a few instances, textures are observed that suggest "sulphurization" of earlier-formed Fe—Ni bearing silicates. In addition to the sulphides, early magmatic chromite is present. The oxide is more prevalent in the dunite and the hartzburgite.

A number of unusual mineralogical features have been observed among the sulphides and these will be referred to specifically in the following descriptions.

The ore minerals observed in polished sections are as follows:

1. *Oxides and Hydroxide*

Magnetite, Fe_3O_4
Chromite, (FeMg) Cr_2O_4
Goethite, FeO(OH)

2. *Nickel-Bearing Sulphides*

Pentlandite, (FeNi)S
Millerite NiS
Heazelwoodite Ni_3S_2
Violarite $(NiFe)_3S_4$

3. *Copper- and Copper-Iron Sulphides*

Chalcocite, Cu_2S
Covellite, CuS
Digenite, Cu_7S_4
Bornite, Cu_5FeS_4
Cubanite, $CuFe_2S_3$
Chalcopyrite, $CuFeS_2$

4. *Iron Sulphides*

Marcasite, FeS_2
Mackinawite, FeS
Pyrrhotite, $Fe_n S_{n+1}$

5. *Elements*

Copper Cu
Awaruite, Ni_3Fe

Magnetite

This mineral derives from the iron released from the breakdown of mafic silicates during serpentinization within each of the rock types. It is thus a "secondary" or "reaction" magnetite.

The magnetite forms narrow filaments, vermiform bodies and irregular patches either within or along the borders of areas of serpentine. Secondary magnetite also occurs within serpentine--filled veinlets that traverse otherwise unaltered areas of the host rock; some degree of mobile movement of the iron oxide is therefore evident.

Magnetite is not uncommon along cleavages and transverse fractures in orthopyroxene where incipient serpentinization has occurred.

Some of the magnetite filaments show much distortion indicating a stress condition during the alteration process.

Chromite

Chromite is relatively abundant and occurs as anhedral to subhedral grains up to 3 mm in diameter.

An occasional chromite grain is completely surrounded by pentlandite in such a way as to suggest nucleation of the sulphide by earlier-formed chromite (Fig. 3). Brittle fracturing is evident in many of the chromite grains and the fractures are sometimes filled with pentlandite. Such fractures are either of irregular shape or are in two intersecting sets which may be structural planes of the chromite or may be the response of a directed stress within the host rock (Fig. 4). A few chromite grains carry copius anhedral to subhedral inclusions of pentlandite with uniform dimensions of about 0.1 mm.

Many of the chromite grains have a narrow outer zone marked by much minute pitting. This is apparently a compositional zoning involving a variation in the Fe:Mg ratio. There is also a faint variation in reflectivity between the inner and the outer zones.

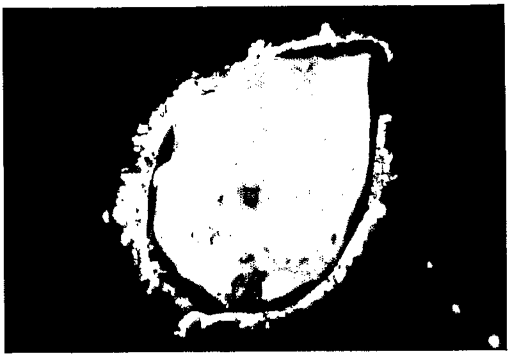

Fig. 3. Magnetite surrounded by pentlandite which the magnetite appears to have nucleated. X 30

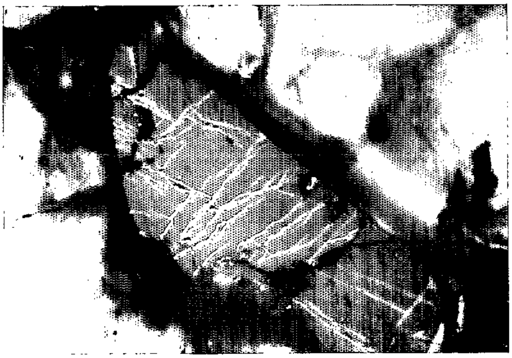

Fig. 4. Chromite with structurally alligned lamellae of pentlandite. X 30

Goethite

The hydroxide of iron occurs as an alteration product of pentlandite and possibly of pyrrhotite. This alteration, observed as it is in otherwise fresh ore, may have taken place in the post magmatic stage. All stages of alteration, from an incipient stage of a network of veinlets of goethite in pentlandite, up to complete replacement can be seen. Elsewhere, heavily fractured pentlandite is criss-crossed by a maze of tiny goethite veinlets as infillings without evidence of replacement.

In a few instances grains of pentlandite show progressive alteration to violarite and the violarite to goethite. Thus part of the grain is pentlandite, part is violarite and part is goethite with various gradations between.

Goethite can be observed, also, as infillings in fractures in orthopyroxene and as occasional irregular grains, up to 0.05 mm, embedded in the orthopyroxenite rock. The mineral in these instances, derives from the hydration of reaction magnetite.

Pentlandite

There are three generations of pentlandite. The principal one is that of discrete grains embedded in the host rock; the second arises from the *early* sulphurization of nickel contained in olivine and in orthopyroxene and is controlled by the crystal structure of these minerals; the third is derived from the *later* sulphurization of the nickel released from the silicates during partial serpentinization.

The early magmatic pentlandite occurs as irregular-shaped grains, grain aggregates and disseminations ranging from a few microns up to 5 mm across. The larger grains are often associated with millerite (q.v.); thus pentlandite frequently forms the core to areas of millerite. These intergrowths range from small subhedral grains embedded in sizeable areas of millerite to larger pentlandite areas bordered, in vein-like fashion, by millerite (Fig. 5). In most instances, however, the pentlandite occurs as isolated individual grains or grain aggregates embedded, alone, in the orthopyroxenite, and rarely in the other rocks, especially within the interstices of silicate minerals.

Fig. 5. Vein-like area of millerite with an inner area of pentlandite. X 25

Throughout the rocks are numerous microscopic fractures which are invariably filled with pentlandite or complex intergrowths of pentlandite, heazelwoodite, millerite, chalcocite and chalcopyrite.

Many of the grains of orthopyroxene and chromite carry structurally aligned bodies of pentlandite. In the case of the orthopyroxene thin lamellae of pentlandite are frequently found along the cleavage directions, and sometimes within cross fractures, of the silicate mineral (Fig. 6 and 7).

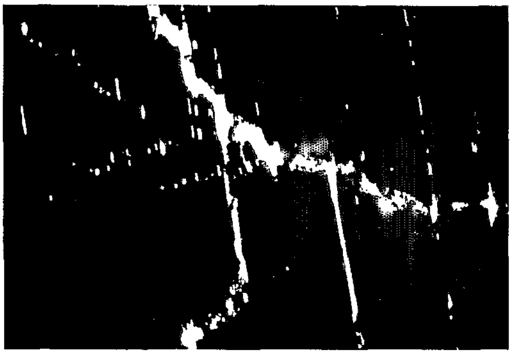

Fig. 6. Pentlandite aligned along structure planes of enstatite. X 50

Fig. 7. Pentlandite along cleavage directions and as irregular inclusions in enstatite. X 30

Some olivine grains carry small trains of pentlandite lamellae which appear to be orientated along growth zones within the silicate mineral (Fig. 8). Euhedral pentlandite crystals (showing an elongated pseudohexagonal outline) are observed occasionally in the groundmass of the rock (Fig. 9). These crystals are certainly synmagmatic in origin. Very rarely, pentlandite forms composite grains with pyrrhotite embedded in pyroxene or interstitial to pyroxene crystals.

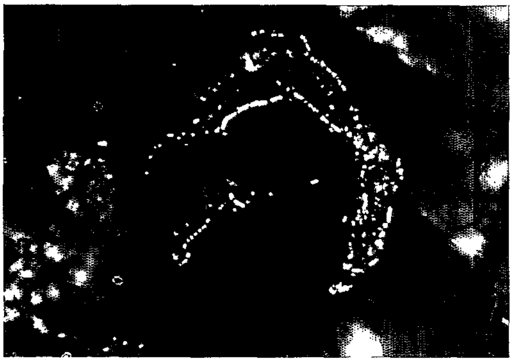

Fig. 8. Pentlandite lining growth zones in olivine. X 50

Fig. 9. Elongated pseudo-hexagonal crystals of pentlandite in pyroxenite. X 75

The occurrence of euhedral to subhedral pentlandite grains embedded in chromite (see under "Chromite") indicates that some pentlandite commenced to form quite early in these rocks. This belief is supported by the absence of evidence suggesting that the pentlandite bears a metasomatic relationship to the chromite.

Particular mention should be made of the frequent, and intimate, association of pentlandite and chalcocite as discussed under the heading for chalcocite.

Orthopyroxene, as well as olivine, shows partial alteration to serpentine along cleavages or along intersecting fractures. These are often filled with narrow films of pentlandite. The pentlandite derives from the sulphurization of the silicate mineral during serpentinization. Thus ions of Fe^{++} and Ni^{++} are released from the mafic minerals which then become hydrated to form serpentine (ca·$Mg_3SiO_5\cdot(OH)_4$). Sulphur combines with the released iron and nickel to form pentlandite (Fig. 10).

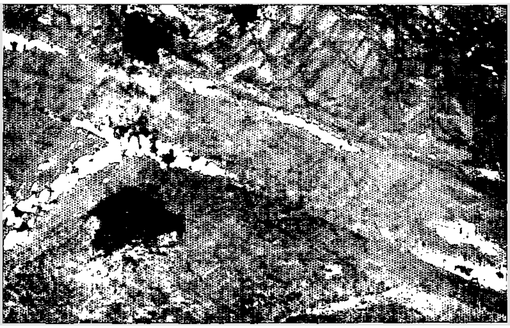

Fig. 10. Pentlandite forming a border to a serpentinite-filled fracture in pyroxenite. X 30

Many of the larger grains of pentlandite show a regular intergrowth with millerite and heazelwoodite such that these minerals occupy the (111) or, less commonly, the (100) structure planes of the pentlandite. In some instances, at least, this may represent alteration of the pentlandite along predetermined structural directions.

The nickel-iron sulphide forms composite grains in which it may be intergrown with one ore more of the following: chalcocite, chalcopyrite, millerite and, less commonly, heazelwoodite, bornite and digenite. In this complex assemblage millerite and heazelwoodite may well be alteration products, in part, of the pentlandite.

Pentlandite is occasionally altered to violarite and thence to goethite. This alteration is patchy and never spreads throughout a given grain.

A feature of some of the pentlandite is the abundant exsolution lamellae and asterisk-shaped bodies of mackinawite within the nickel mineral, (q. v.).

The association of pentlandite and chalcocite in juxtaposed serpentine-filled fractures in mafic silicates is noteworthy. In the process of serpentinization only sufficient iron was released in some instance, to satisfy the composition of pentlandite $(FeNi)S$, so that simultaneously released copper formed chalcocite Cu_2S rather than the more typical chalcopyrite $CuFeS_2$.

Millerite

Millerite is a relatively abundant mineral which, together with heazelwoodite, ranks next to pentlandite in amount. It occurs as irregular shaped grains up to 1 mm across occasionally on its own but more commonly surrounding cores of pentlandite. Such composite grains range from a 50:50 ration of the two minerals to a ratio of 70 per cent pentlandite: 30 per cent millerite. Millerite often surrounds areas of pentlandite in unaltered rock in such a manner as to indicate that as the availability of iron decreases millerite develops at the expense of pentlandite.

Millerite also occurs as an exsolution product of pentlandite where narrow lamellae of the former are contained in parallel structure planes of the latter (Fig. 11).

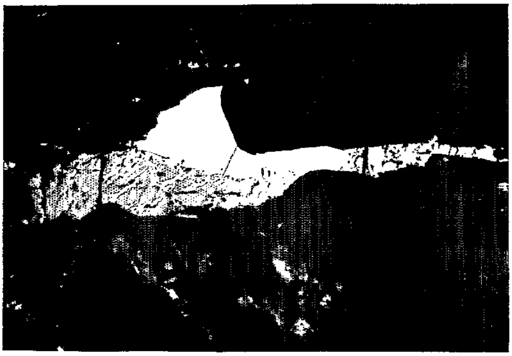

Fig. 11. Millerite (white) with pentlandite (grey) from which some millerite has exolved as narrow parallel lamellae. X 40

Millerite accompanies pentlandite, plus minor amounts of chalcopyrite, in narrow veinlets (some no more than 0.005 mm wide) occupying fractures in the orthopyroxenite. Minute particles of millerite are occasionally observed in orthopyroxene and sometimes form very slender lamellae along the cleavages of that mineral.

Many of the large grains of pentlandite carry numerous narrow subparallel lamellae of millerite often normal to the elongation of the grain of pentlandite. This may represent the breakdown of pentlandite to millerite along structure planes during the post magmatic stage. Secondary millerite is also seen in some of the pentlandite areas as a close-fitting mosaic of irregular shaped grains within pentlandite. The texture (Fig. 12) is obviously one in which pentlandite is breaking down to millerite.

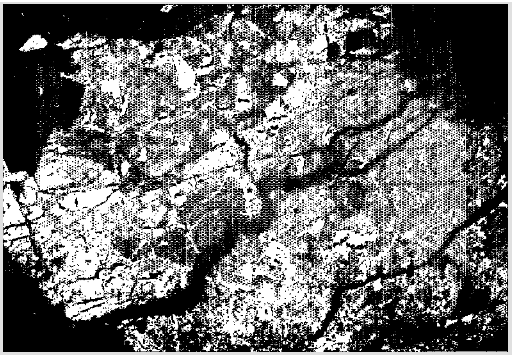

Fig. 12. Pentlandite almost completely replaced by a mosaic of irregular shaped grains of millerite. Crossed polars. X 25

The most unusual mode of occurrence of millerite is that of small grains adjacent to inclusions of chalcopyrite within pentlandite. These inclusions of chalcocite within pentlandite give rise to reaction rims one of the resulting products of which is "reaction millerite". This is more fully described under *chalcocite* (q. v.).

There are thus four generations of millerite as follows:

(a) As a minor primary-magmatic product,

(b) As a late or post magmatic alteration of pentlandite,

(c) As a reaction product between pentlandite and chalcocite,

(d) As exsolution lamellae within pentlandite.

Heazelwoodite

This mineral ranges next to pentlandite and millerite in abundance. It occurs mainly in association with pentlandite and millerite and appears, in most instances, to have formed from the alteration of pentlandite. Pentlandite is sometimes rimmed by heazelwoodite and this mineral may also be seen as small alteration patches in larger areas of pentlandite.

Heazelwoodite is readily recognised by its bright polarization colours of greyish-blue, green and lilac disposed in a characteritic mosaic pattern.

Violarite

Violarite appears always to be an alteration product of pentlandite — presumably in the post magmatic stages.

Some of the larger pentlandite grains (Fig. 13) show patches, up to 0.5 mm, of turbid material having a vague purplish tint. This mineral does not polish readily and appears to be incipient alteration of pentlandite to violarite. Elsewhere, pentlandite shows definite alteration to purplish-coloured violarite along narrow zones — mostly cleavage directions. These zones of alteration can be observed spreading outwards and giving rise to larger areas of alteration. Alteration may occur also in small irregularly-shaped patches within the pentlandite grains.

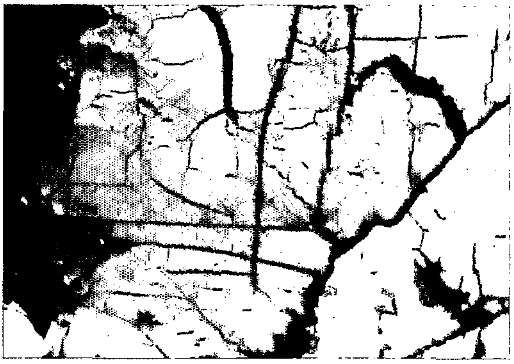

Fig. 13. Pentlandite partly altered to violarite (turbid appearance) X 25

Alteration of pentlandite to violarite is sometimes "selective" such that in an aggregate of juxtaposed pentlandite grains some grains remain quite unaltered while others are completely converted to violarite.

Violarite, itself, sometimes shows incipient alteration to goethite. This alteration proceeds, initially, along directions that are relic cleavages of the original pentlandite.

Chalcocite

This copper sulphide is a prominent constituent of many of the polished sections where, as a definite, primary, magmatic mineral it occurs in intimate association with pentlandite and as small monomineralic grains in the interstices between silicate minerals.

In addition to the various intergrowths of chalcocite and pentlandite (see below), the copper sulphide may be intergrown with either bornite or chalcopyrite and occasionally both. Some chalcocite grains carry very minute exsolution lamellae of bornite and others carry equally minute exsolution bodies of chalcopyrite; a few grains were noted in which both bornite and chalcocyte occur as exsolution bodies. Irregular shaped intergrowth of these three minerals also occur. Chalcocite is present sometimes as narrow exsolution lamellae in small bornite grains and likewise in small chalcopyrite grains.

Three particular intergrowths involving chalcocite are especially noteworthy. First is the intergrowth of lamellae of chalcocite within the (100) planes and in certain other planes, in the pendlandite. This does not appear to be mere migration of chalcocite along structural planes in the pentlandite but may be a structurally controlled simultaneous precipitation of the two sulphides (Fig. 14).

The second texture of note is that of an eutectic intergrowth between chalcocite and pentlandite (Fig. 15). It is evident that, at a certain proportion of pentlandite to chalcocite, and at a certain temperature, both sulphides precipitate together in a classic eutectic pattern.

The intimate intergrowth of pentlandite and chalcocite sometimes results in the solid-state reaction of these two minerals to form chalcopyrite and millerite. Such a reaction rim is seen in Fig. 16, where a roundish grain of chalcocite, carrying minute particles of digenite, is

Fig. 14. Pentlandite with orientated lamellae of chalcocite (grey) possibly due to structurally controlled simultaneous crystallization of the two sulphides. 75

Fig. 15. Eutectic intergrowth of pentlandite (white) and chalcocite (grey) within a larger area of pentlandite. X 75

embedded in an area of pentlandite. Fe^{++} ions have migrated into the chalcocite to form a narrow border of chalcopyrite leaving scattered particles of the iron-free nickel sulphide millerite.

By a process of reduction small grains of chalcocite can also be seen altering to native copper. Chalcocite is also observed on occasion, intergrown with covellite (q.v.) including the areas surrounding native copper.

Covellite

Covellite is a minor accessory and is found mainly as an intergrowth with chalcocite and, on rare occasions in association with traces of digenite, as isolated units within the orthopyroxenite.

Covellite is also present in those zones where chalcocite is breaking down to native copper. Some of the covellite, however, appears to be primary.

Digenite

This copper sulphide occurs in trace amounts only, embedded in areas of chalcocite (Fig. 16). It is also present, rarely, as tiny inclusions and as minute particles attached to the outer margins of grains of pentlandite; small amounts of covellite are usually associated.

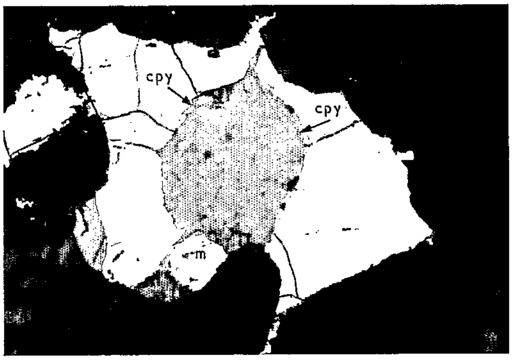

Fig. 16. Oval shaped area of chalcocite (grey) with minute grains of digenite (dark grey spots) included in an area of pentlandite (whitish). A solid state reaction between the chalcocite and the pentlandite has produced a narrow reaction rim of chalcopyrite (cpy) around the chalcocite. Some millerite (m) has also been produced. X 50

Bornite

Bornite is an accessory mineral which occurs as dispersed grains of small dimension and irregular shape, embedded in the rock. It is usually associated with chalcopyrite and with traces of chalcocite.

Bornite may show various exsolution lamellae of chalcopyrite or, conversely, may occur as narrow exsolution lamellae in chalcopyrite i.e. bornite may be either solvent or solute with respect to chalcopyrite. It occurs similarly as a mutual exsolution product with chalcocite where either may act as host.

Cubanite

Cubanite was observed as exsolution lamellae in millerite. The lamellae consist of relatively broad, parallel-sided units traversing the entire width of the millerite host and in habit closely resembles the well known exsolution lamellae of cubanite in chalcopyrite.

It is evident, from this intergrowth that cubanite can enter into solid solution in millerite at elevated temperatures.

Chalcopyrite

The incidence of chalcopyrite parallels that of bornite. In addition, chalcopyrite occurs sparingly as small monomineralic grains within the orthopyroxenite and, in association with pentlandite and millerite, as minute veinlets traversing the rock.

Particular mention is again warranted of the narrow rims of "reaction chalcopyrite" formed by diffusion reaction between chalcopyrite and pentlandite.

Marcasite

A few specimens show incipient development of small patches of marcasite. The iron disulphide appears to result from the partial breakdown of pentlandite and occasionally of sparse pyrrhotite.

Mackinawite

Some grains of pyrrhotite are liberally endowed with minute skeletal shaped exsolution bodies of mackinawite. In the same specimens narrow lamellae of mackinawite have exsolved along structure planes of the solvent making intersecting sets at ca. 120° to one another (Fig. 17). The mineral exhibits bright blue, pinkish to brownish-white and reddish-brown polarization colours and intense reflections pleochroism. These optical properties point to mackinawite rather than valleriite.

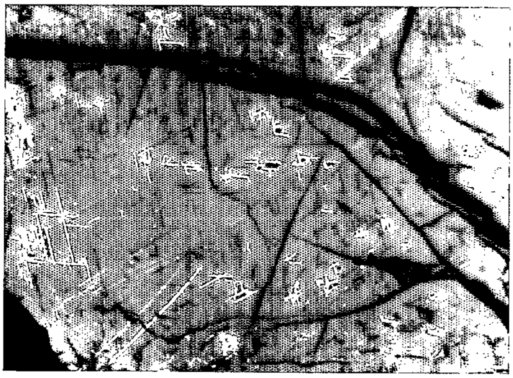

Fig. 17. Orientated lamellae of mackinawite as an exsolution product from pentlandite. Polars half crossed. X 40

A particular occurrence of what appears to be mackinawite, is an exsolution lamellae, barely one micron wide, lying transverse to the elongation of the exsolution lamellae of cubanite in millerite. Thus millerite has exsolved cubanite on cooling and the cubanite has further exsolved mackinawite.

Pyrrhotite

This mineral is only sparsely developed in these rocks — only a few isolated grains having been observed.

Certain patches of marcasite, of small extent, associated with pentlandite may have been derived from pyrrhotite. The granular texture is rather typical of the breakdown of pyrrhotite to marcasite.

In one instance several sizeable grains of pentlandite show partial alteration to violarite, the violarite, in turn, is partially replaced by a network of goethite veinlets. The small intervening areas between the goethite in one of the grains is strongly anisotropic with polarization colours that typify pyrrhotite. This occurrence is almost certainly pyrrhotite.

Copper

In several specimens areas of chalcocite, with traces of covellite, adjacent to grains of pentlandite, have cores of elemental copper. The copper has a ragged outline against the enclosing chalcocite while the sulphide itself also has ragged outlines. The shapes of these grains is not incompatible with a supergene origin. The overall amount of copper is very minor.

Awaruite

One of the most interesting, and unusual, paragenetic associations is that of awaruite with a composition, determined by electron probe, of Ni74, Fe26 per cent. Only a few grains were observed and these were embedded in heazelwoodite near the junction of that mineral with pentlandite. It is white with a faint cream overtone, possesses about the same polishing hardness as pentlandite and is quite isotropic (Fig. 18).

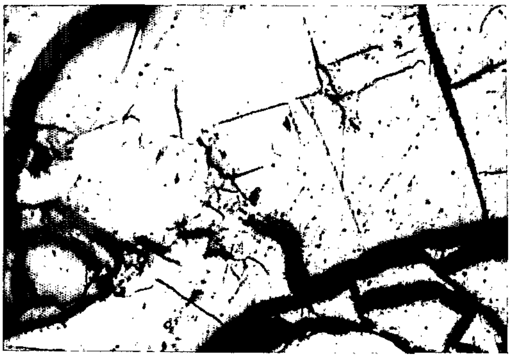

Fig. 18. Awaurite (white) in millerite. X 75

The occurrence of a bimetallic compound indicates that small "domains" existed within the rock where a sulphur deficient environment eventually prevailed.

Discussion

Sulphides of nickel, iron and copper as well as native copper, chromite and awaruite are present as accessory minerals over a wide areal and vertical extent in the ultramafic rocks of New Caledonia. They are sparsely disseminated in the rocks without any indication of such concentration as would suggest low grade economic proportions.

The following ratios as between nickel-bearing sulphides, copper-bearing sulphides and iron sulphides are estimated as follows:

Ni : Cu : Fe :: 95 : 4 : 1

There is a considerably greater concentration of sulphides in the pyroxenite layers (though still in accessory amounts) than in the hartzburgite layers. Nickel sulphides, however, may sometimes reach a similar concentration in the hartzburgite to that in the pyroxenite though copper sulphides are always in mere traces in rocks other than pyroxenite.

Chromite crystallized early in the cooling of the host rocks. The euhedral inclusions of pentlandite in chromite suggests that some of the nickel-iron sulphide formed early but the main period of sulphide formation was delayed until the sulphur vapour pressure was sufficient to allow the elements to diffuse through the crystallizing magma. The numerous minute particles of sulphides seen in the interstices of the silicate minerals suggests the presence of some sulphur in the early magmatic stage. However, the frequency with which sulphides occur in small fractures in the rock and along cleavages in already-formed pyroxenes (c.f. Figs. 6 and 7) evidences a main period of sulphide formation toward the end of silicate crystallization. Indeed there is reason to believe that sulphides were still mobile enough to migrate into brittle fractures after the main rock mass had completely consolidated. Thus "primary" or magmatic sulphides were formed over a period ranging from *early-magmatic* to *epi-magmatic*.

At some later time *post-magmatic* processes, initiated by the surgence of water vapour, caused partial serpentinization even to the extent of microscopic serpentine-filled fractures. Sulphides, including pentlandite, line these fractures (c.f. Fig. 10). Therefore in the breakdown of a nickel-rich forsteritic olivine Ni and Fe ions were released to form, respectively *secondary* pentlandite and *secondary* magnetite. In this process it is evident that sulphur was still circulating or had been "re-activated" after condensation following the magmatic stages.

It is probable that certain processes shown in the sulphides, and perhaps of a "retrograde" nature, occurred during serpentinization. These include:

i. pentlandite → violarite → goethite
ii. pentlandite → millerite
iii. pentlandite → heazelwoodite → awaruite
iv. chalcocite → native copper
v. pentlandite + chalcocite
  → chalcopyrite + millerite

It will be noted (Fig. 14) that in some circumstances pentlandite and chalcocite are stable in what appears to be unaltered rock. At other times (Fig. 16) a diffusion reaction occurs between the two minerals; disturbance of equilibrium during metamorphism of the host rock may have facilitated this diffusion reaction.

The formation of garnierite and other nickel silicate ores in New Caledonia appears to be influenced (*inter alia*) by the following factors (TRESCASES, 1969):

i. composition of the original rocks
ii. climate
iii. physiography

This involves chemical alteration of olivine-rich, nickel-bearing rocks at or near the surface under tropical conditions. There appears to be a process akin to weathering and to serpentinization interacting to form the garnieritic ores as recognised by GARNIER in 1867.

It has been the general belief that the nickel content of the garnieritic ores was derived from the nickel in the silicate minerals of the ultramafic rocks particularly the olivines and, to a lesser extent, the pyroxenes. This is certainly true but it is now evident that a small proportion of the nickel of the garnieritic ores probably derives from Ni ions released from nickel sulphides contained in the ultramafic rocks. Most of the nickel of the silicates, together with magnesium and silica, goes into garnierite as does the nickel of the sulphide minerals. The iron so released, together with small amounts of nickel goes into nickeliferous laterites which are widespread in New Caledonia. The sulphur from the sulphides would be dissipated in this process.

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